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Current Status of Alternative Automotive Power Systems and Fuels Volume I. Executive Summary

Aerospace Corp, El Segundo, Calif Environmental Programs Group

Prepared for

Environmental Protection Agency, Ann Arbor, Mich

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CURRENT STATUS OF ALTERNATIVE AUTOMOTIVE POWER SYSTEMS AND FUELS VOLUME I - EXECUTIVE SUMMARY

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Office of Air and Waste Management
Office of Mobile Source Air Pollution Control
Alternative Automotive Power Systems Division
Ann Arbor, Michigan 48105

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16. ABSTRACT

A summarization has been made of the available nonproprietary information on the technological status of automotive power systems which are alternatives to the conventional internal combustion engine, and the technological status of non-petroleum-based fuels derived from domestic sources which may have application to future automotive vehicles. The material presented is based principally upon the results of research and technology activities sponsored under the Alternative Automotive Power Systems Program which was originated in 1970. Supplementary data are included from programs sponsored by other government agencies and by private industry. The results of the study are presented in four volumes; this volume presents a concise view of important findings and conclusions for three topical areas: Alternative Automotive Heat Engines, Alternative Nonpetroleum-Based Automotive Fuels, Electric and Hybrid Power Systems.

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Prepared by

The Environmental Programs Group

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Contract No. 68-01-0417

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U.S. ENVIRONMENTAL PROTECTION AGENCY
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Office of Mobile Source Air Pollution Control
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Publication No. EPA-460/3-74-013-a

FOREWORD

This report, prepared by The Aerospace Corporation for the Environmental Protection Agency (EPA), Alternative Automotive Power Systems Division, summarizes available nonproprietary information on the technological status of automotive power systems which are alternatives to the conventional internal combustion engine, and the technological status of nonpetroleum-based fuels derived from domestic sources which may have application to future automotive vehicles.

The status of the technology reported herein is that existing at the end of 1973 with more recent data in selected areas. The material presented is based principally upon the results of research and technology activities sponsored under the Alternative Automotive Power Systems (AAPS) Program which was originated in 1970 and which is administered by the Alternative Automotive Power Systems Division of EPA. Supplementary data are included from programs sponsored by other government agencies and by private industry. Additional information on technology and development programs is known to the government but cannot be documented herein because the data are proprietary.

One purpose that the AAPS Program serves is to provide a basis of knowledge and perspective on what can and cannot be accomplished with the use of alternative propulsion and fuels technology, and to disseminate this information to Congress, Federal policy makers, industry, and the public. Thus, the publication of information such as that contained herein is in keeping with this element of the mission of the AAPS Program. This is the first of a series of reports on alternatives that are intended to be published annually.

The results of this study are presented in four volumes and three main topical areas:

Volume I.	Executive Summary
Volume II.	Alternative Automotive Engines

Volume III.	Alternative Nonpetroleum-Based Automotive Fuels
Volume IV.	Electric and Hybrid Power Systems

Volume I, the Executive Summary, presents a concise view of important findings and conclusions for all three topical areas. Thus, an overview of the study results may be obtained by reading Volume I only. Volumes II, III, and IV contain detailed, comprehensive discussions of each topical area and are therefore of interest primarily to the technical specialist. Each of these three volumes also contains Highlights and Summary sections pertaining to the topical area covered in the volume.

ACKNOWLEDGMENTS

Appreciation is acknowledged for the guidance and assistance provided by Mr. Graham Hagey of the Environmental Protection Agency (EPA), Alternative Automotive Power Systems (AAPS) Division, who served as EPA Project Officer for this study. Appreciation is also extended to staff members of the AAPS Division, to other EPA divisions, to personnel of various government agencies, and to those in industry and the academic community who supplied reference material and reviewed the contents of this report. In particular, the information provided by Exxon Research and Engineering Company and the Institute of Gas Technology during their contractual study efforts for EPA has been a valuable contribution to sections of the report on alternative nonpetroleum-based fuels.

The many technical personnel of The Aerospace Corporation who made valuable contributions to the effort performed under this contract are acknowledged in the specific volumes to which they contributed.

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INTRODUCTION

In the first 20 years of this century, many different power systems were in competition as an automotive powerplant. The three major competitors were battery-powered electric systems, steam engines (Rankine cycle), and spark ignition internal combustion engines (Otto cycle). Many production versions of each type of system were on the market and at least one manufacturer offered versions of all three systems (apparently more uncertain of the final outcome than other manufacturers). It is well known that the Otto cycle system eventually won out. Although occasional attempts have been made over the last 50 years to bring out new versions of electric vehicles and steam engines, none have yet offered serious competition to the Otto cycle engine and, in fact, few have been marketed.

Perhaps the most significant past effort to develop an alternative powerplant for passenger cars was that sponsored by the Chrysler Corporation on gas turbines. After nearly 20 years of research and a considerable investment of manpower and resources, this effort culminated in a 50-car fleet of gas turbine-powered vehicles tested by consumers throughout the United States starting in 1964. Following evaluation of these tests, a corporate decision was made not to proceed with turbine production and it appeared that the Otto cycle engine would continue its dominant position as the powerplant for automobiles.

However, events would soon overtake any complacency on the part of those satisfied with maintaining the status quo. By the late 1960's, the public was becoming much more aware of the rapidly deteriorating air quality in large urban areas in this country. At the same time, the Congress grew increasingly impatient with existing regulatory programs for control of automobile-caused air pollution. Exhaust emissions from the internal combustion engine in automobiles had long been singled out as the primary cause of smog and more stringent control of emissions from this source appeared warranted.

It was late in 1969 when members of the President's Office of Science and Technology, then headed by Dr. Lee DuBridge, expressed their environmental concern to the President. It was stated that because of the automobile's significant contribution to the nation's deteriorating air quality, the exhaust emission standards required in future years--through the end of this century--might have to be so stringent as to preclude the clean up of the conventional Otto cycle engine. To alleviate the potential impact of such events and to provide assurance to the nation that technologies relating to other types of power systems would be available, if needed, a Federal program of research and technology development was recommended.

The President announced the program in his Message on the Environment early in 1970. That program, called the Alternative Automotive Power Systems (AAPS) Program,[1] is managed by the Environmental Protection Agency (EPA) in Ann Arbor, Michigan. The program was focused initially on power systems that offered the potential of being inherently clean compared with the conventional Otto cycle engine. In 1972 the program scope was broadened and energy efficiency was elevated to equal importance with low automobile exhaust emissions. Investigations on the use of alternative fuels (nonpetroleum derived) were also included at that time.

The present report concerns the developments in alternative powerplants as related to the conventional Otto cycle engine, and in alternative nonpetroleum-based fuels as related to petroleum-derived gasoline. The objective of the report is to summarize the available information on the technological status of alternatives for future automotive vehicles. As such, then, it serves to document the results from the many past and present activities of the AAPS Program, as well as to provide similar information from programs sponsored by other government agencies and by private industry.

[1] Originally called the Advanced Automotive Power Systems Program.

The significant findings with regard to technological status are summarized herein under the category headings of:

- Alternative Automotive Heat Engines
- Alternative Nonpetroleum-Based Automotive Fuels
- Electric and Hybrid Power Systems.

ALTERNATIVE AUTOMOTIVE HEAT ENGINES

As used herein the term 'heat engine' applies to the category of engines in which heat is converted in some form to work in order to provide power to the wheels of a vehicle. The heat engine then is the prime mover. The source of heat is generally the combustion of a fuel in air.

Several different types of heat engines for use in automobiles have demonstrated the ability to provide desired power levels while simultaneously offering the potential for major reductions in exhaust emissions when contrasted with the conventional spark ignition engine. In some cases, an engine has been characterized as having the potential to meet the original 1975 Federal emission standards [hydrocarbons (HC) = 0.41 grams per mile (gm/mi), carbon monoxide (CO) = 3.4 gm/mi, oxides of nitrogen (NO_x) = 3.1 gm/mi)] or the original[1,2] 1976 Federal emission standards (HC = 0.41 gm/mi, CO = 3.4 gm/mi, NO_x = 0.4 gm/mi) without extensive after-treatment or add-on devices. Each engine, however, has certain design and performance deficiencies that remain to be overcome (e.g., excessive size, high manufacturing cost, prolonged startup time). Recently, the concern over conservation of energy resources has prompted additional effort in the areas of reduction in engine fuel consumption and verification of flexibility in operation with a wide range of possible fuels. This is exemplified, as noted previously, by early modifications within the EPA AAPS Program to stress fuel consumption reduction as well as achievement of emission levels consistent with Federal standards.

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[1] Interim standards with relaxed requirements are now in effect.

[2] Note that emission goals for the AAPS Program were set at one-half the original 1976 standards to ensure compliance under production and in-service conditions.

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DEVELOPMENT STATUS OF ALTERNATIVE HEAT ENGINES

The following highlights summarize the status of development work on alternative engines investigated in recent years. The engines reviewed are the gas turbine, Rankine cycle, Stirling cycle, Diesel cycle, Wankel (and other rotary piston designs), and Otto cycle (using stratified charge combustion). These engine types are in various stages of development, ranging from redesign of engines under limited production to early research and mid-term development efforts on engines at least eight to ten years from full production (if placed in a production program status).

Gas Turbine Engines

1. Until recently, the exhaust emissions of automotive-type gas turbine engines have been typified as characteristically low in unburned hydrocarbons and carbon monoxide, but with NO_x levels too high to permit attainment of the original 1976 Federal emission standard of 0.4 gm/mi. For example, Chrysler's sixth-generation engine installed in an intermediate-size vehicle (Figure 1) has NO_x emissions of about 2.2 gm/mi over the Federal Emissions Test Driving Cycle. A summary tabulation of emissions from gas turbine combustors and systems appears in Table 1.

2. As part of the AAPS Program, Solar, a Division of International Harvester, has recently developed a new gas turbine combustion system that, based on steady-state test data, is calculated to be capable of meeting the original 1976 Federal emission standards and is close to meeting the AAPS Program goals (one-half the level of the original standards). Additional development is required to perfect the combustor control system and to validate meeting program goals with transient operation of the engine over the Federal Emissions Test Driving Cycle.

3. Reflecting similar recent advancements, a General Motors-sponsored program resulted in an experimental 225-horsepower gas turbine engine installed in a car meeting the original 1976 Federal emission standards. Complete details concerning engine design and operation are not available.

4. Estimated high production cost is another factor inhibiting the implementation of the automotive gas turbine engine. Other problems involve the need for improvements in noise level, durability, acceleration lag, and fuel economy. These problems are being investigated by Chrysler under a $6.5 million EPA contract awarded in December 1972 for the

Figure 1. Chrysler 150-hp Gas Turbine Engine, Vehicle Installation

Table 1. Gas Turbine Exhaust Emission Data Over the Federal Emissions Test Driving Cycle

Engine/Manufacturer	Emissions (gm/mi)			Remarks
	CO	HC	NO_x	
a. Conventional Combustors				
United Aircraft Research Laboratories RGSS-6	0.53	0.15	2.72	Calculated values over simulated Federal Driving Cycle, based on emission data from GM engine GT-309.
United Aircraft Research Laboratories SSS-10	1.86	0.31	1.03	Calculated values over simulated Federal Driving Cycle, based on emission data from GM engine T-56.
Chrysler sixth-generation engine	3.99	-0.26	2.21	1975 Federal Test Procedure emissions corrected (background level subtracted from measured values).
Williams Research/ WR26/AMC Hornet	7.43 6.92	0.62 0.72	2.8 2.5	Cold start } 1975 Federal Test Hot start } Procedure
Williams Research/ 131Q/Volkswagen	4.5	0.34	1.81	1972 Federal Test Procedure.
b. Advanced Combustors				
Solar	3.34	0.11	0.34	Calculated values for simulated Federal Driving Cycle, based on advanced combustor data.
General Motors 225 HP Regenerative Engine	2.4	0.015	0.315	Experimental test bed engine, chassis dynamometer test with 5,000-lb car, 1975 Federal Test Procedure.
AiResearch	1.6	0.67	0.44	Calculated values for simulated Federal Driving Cycle, for recuperated engine with 10 percent bypass.
United Aircraft of Canada	3.64	0.49	0.52	Calculated values over simulated Federal Driving Cycle based on advanced combustor data.
c. Clean Air Act Requirements	3.4	0.41	0.4	Original 1976 Federal standards

development of an improved version of its sixth-generation engine for powering an intermediate-size car. Engine design for a compact car will be examined in a recent extension to this program. The NASA Lewis Research Center is playing an important role in this effort in the areas of combustion, rotating machinery design and engine test. Figure 2 shows the EPA/Chrysler/NASA team.

5. While demonstrated fuel economy is low for gas turbine engine-powered cars (about eight to nine miles per gallon for an intermediate-size car over the Federal Emissions Test Driving Cycle), it is estimated that by 1975 fuel economy for improved engines will rise to about 12 miles per gallon and be competitive with that of full-size spark ignition engine-powered cars. This improvement is expected to result from a variety of effects as noted in Table 2.

6. In the future, if ceramic turbines are developed, a further substantial rise in turbine operating temperature appears possible, leading to a significant reduction in fuel consumption. For example, it is estimated that a temperature increase at the turbine inlet from a current value of about 1800°F to a future value of 2500°F would result in about a 20 percent improvement in fuel consumption. An additional benefit from the use of ceramics might be reduced manufacturing cost.

Rankine Cycle Engines

1. Under the AAPS Program, the Rankine cycle engine is in an advanced state of development, having progressed to the point where several complete engine systems have been tested on engine dynamometers. Some of these engine systems are water-base working fluid designs (steam engine) that present the problem of fluid freezing at low temperatures. Others rely on an organic-type working fluid as one means of circumventing this problem. The Rankine cycle contractors who have worked on various aspects of the AAPS Program appear in Figure 3.

2. Preliminary analyses of steady-state emission data from the AAPS Program show that the emissions from this type of engine should meet the original 1976 Federal emission standards and that fuel economy can be competitive with current emission-controlled spark ignition engines. A breakthrough in the design of the engine condenser has resulted in much smaller units than in the past and this development has considerably facilitated engine installation into current automobile engine compartments.

3. The task of repeated demonstrations of low emissions in transient operation (including cold start) with a fully automatic control system has been initiated under the AAPS Program. Scientific Energy Systems Corporation has been selected from several competing contractors to provide EPA with a vehicle-installed steam engine system for testing

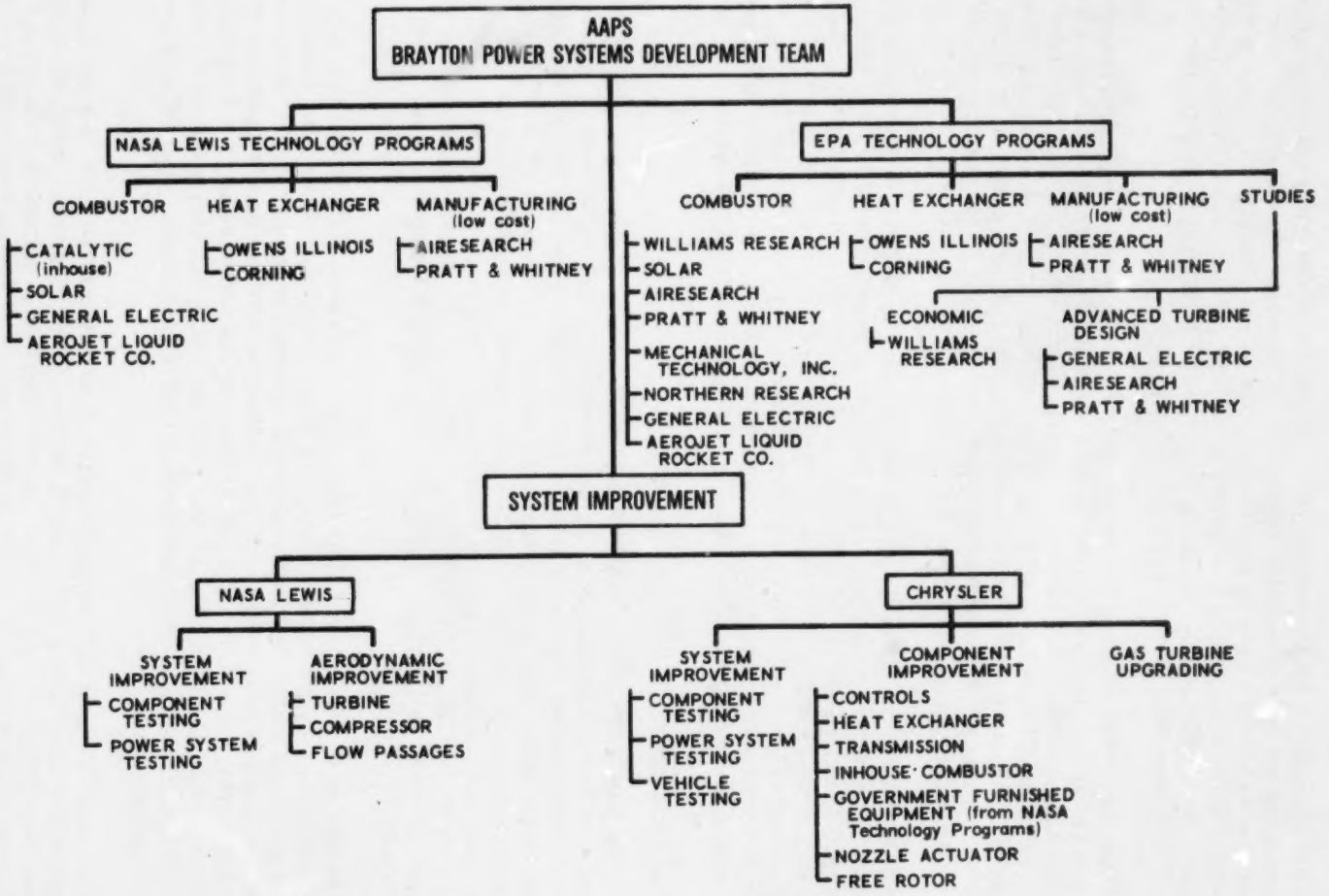

Figure 2. EPA/AAPS Brayton Power Systems Development Team

Table 2. Fuel Economy Improvement Items for Baseline Gas Turbine Development Program

Improvement Item	Improvement Description	Improvement Goal	Estimated Improvement in Tank Mileage
Water Injection (Upstream of Compressor)	Reduced engine size for same horsepower	10% hp	5%
Variable Inlet Guide Vanes	Reduced engine size for same horsepower	12% hp	6 to 8%
Ceramic Regenerator	Better effectiveness	+4%	6%
Higher Cycle Temperature	Reduced engine size for same horsepower	7% hp	5%
Recovery and Reduction of Heat Loss	Reduced parasitic losses	50%	6 to 10%
Power Turbine	Higher efficiency	+2 - 4%	7%
Compressor Turbine	Higher efficiency	+4%	8%
Compressor	Higher efficiency	+1%	2%

hp = horsepower

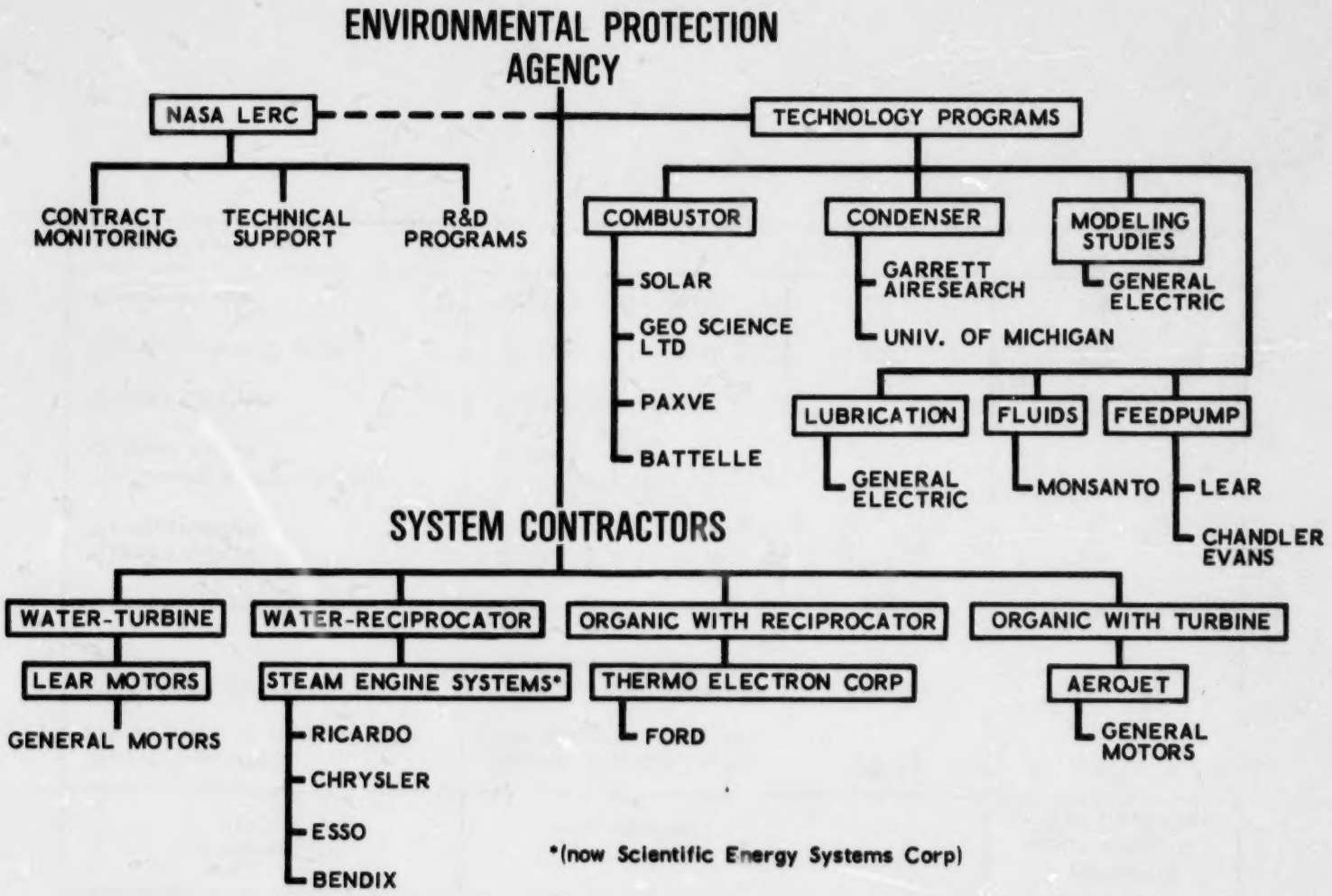

Figure 3. EPA/AAPS Rankine System Development Team

(Figure 4). This engine design utilizes a reciprocating piston expander for transmitting power through a transmission to the rear wheels (in contrast to competing designs based on a turbine expander).

4. Future AAPS program efforts are expected to concentrate on achieving improvements in fuel economy and investigating low-cost production techniques.

5. In addition to the EPA AAPS Program, the U.S. Department of Transportation has investigated Rankine cycle power systems for buses, and the State of California, under the Clean Car Project, has been testing this type of engine for passenger car use. Other domestic and foreign programs are being funded by private capital.

Stirling Cycle Engines

1. Stirling cycle engines have the potential for demonstrating excellent fuel economy, multifuel capability, very low noise and vibration, and emissions low enough to meet the original 1976 Federal emission standards.

2. The most significant advancement in recent times is a major reduction in engine volume, coupled with an increase in power output per pound of engine weight. This has led to the initiation of a Ford demonstration program that involves the installation of engines in Torino and Pinto automobiles. N. V. Philips Laboratories at Eindhoven, Holland, will furnish the engine for the Torino installation (Figure 5), and United Stirling of Sweden will provide the Pinto engine.

3. A summary of emissions and fuel economy projections made by Ford for the Stirling engine appears in Tables 3 and 4. Primary problem areas requiring further development work for resolution are:

   a. For efficient operation of this engine, the radiator in certain designs can be about two and one-half times as large as that for a comparable internal combustion engine. A reduction in radiator size will be necessary to permit satisfactory installation in current automobile engine compartments.

   b. In order to contain the high-pressure hydrogen working fluid, the array of heater tubes is now made of nickel-chrome alloys. These tubes are expensive to fabricate and, therefore, production processes must be improved or new designs must evolve to aid in reducing engine manufacturing costs.

4. Other problems with the Stirling engine include the low life of piston seals, hydrogen diffusion through the cylinder walls and seals, and the need for low-cost power control capable of providing smooth power transitions. Engineering solutions appear available, but they require further development and demonstration.

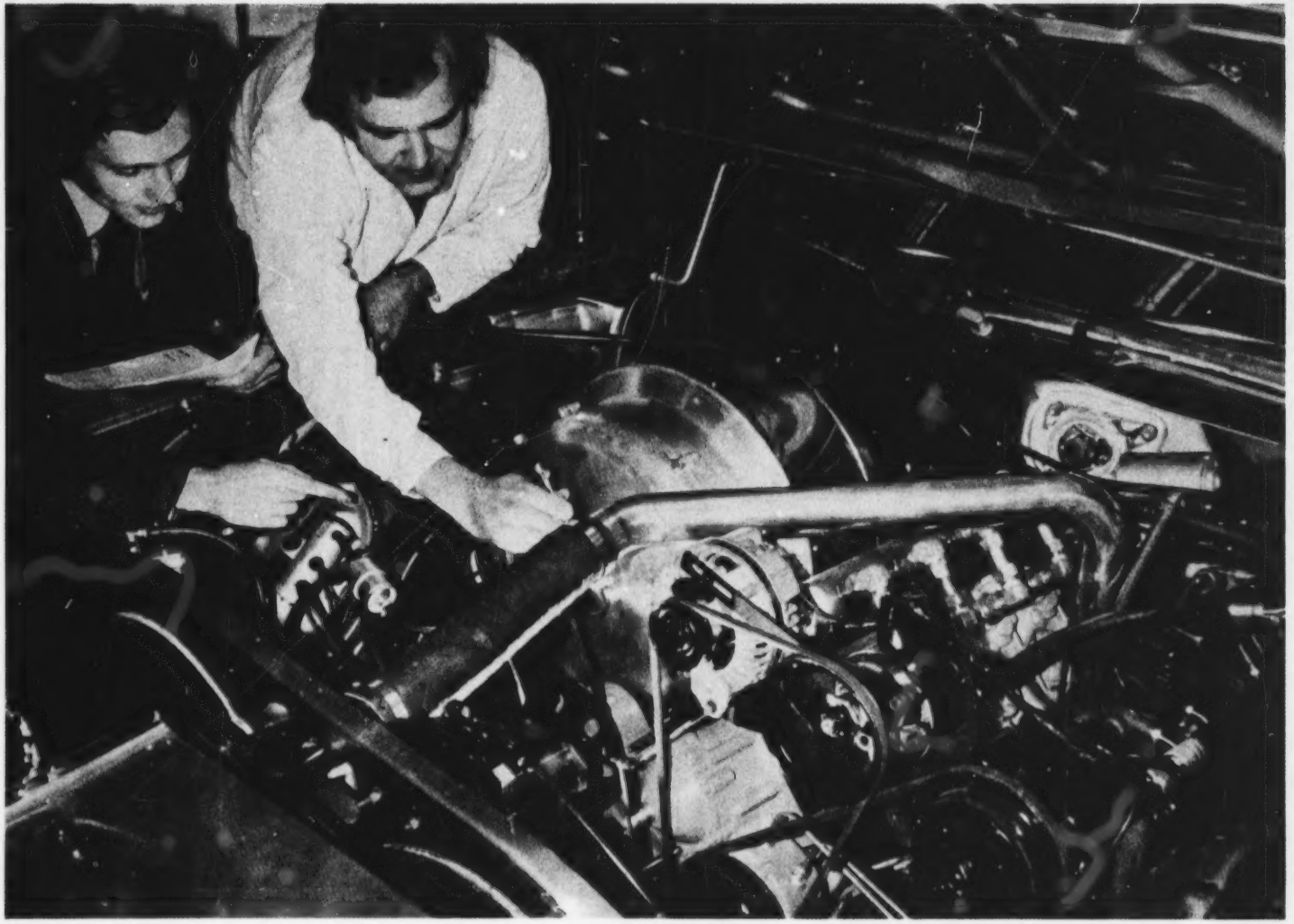

Figure 4. 150-Horsepower Steam Engine (Scientific Energy Systems Corporation)

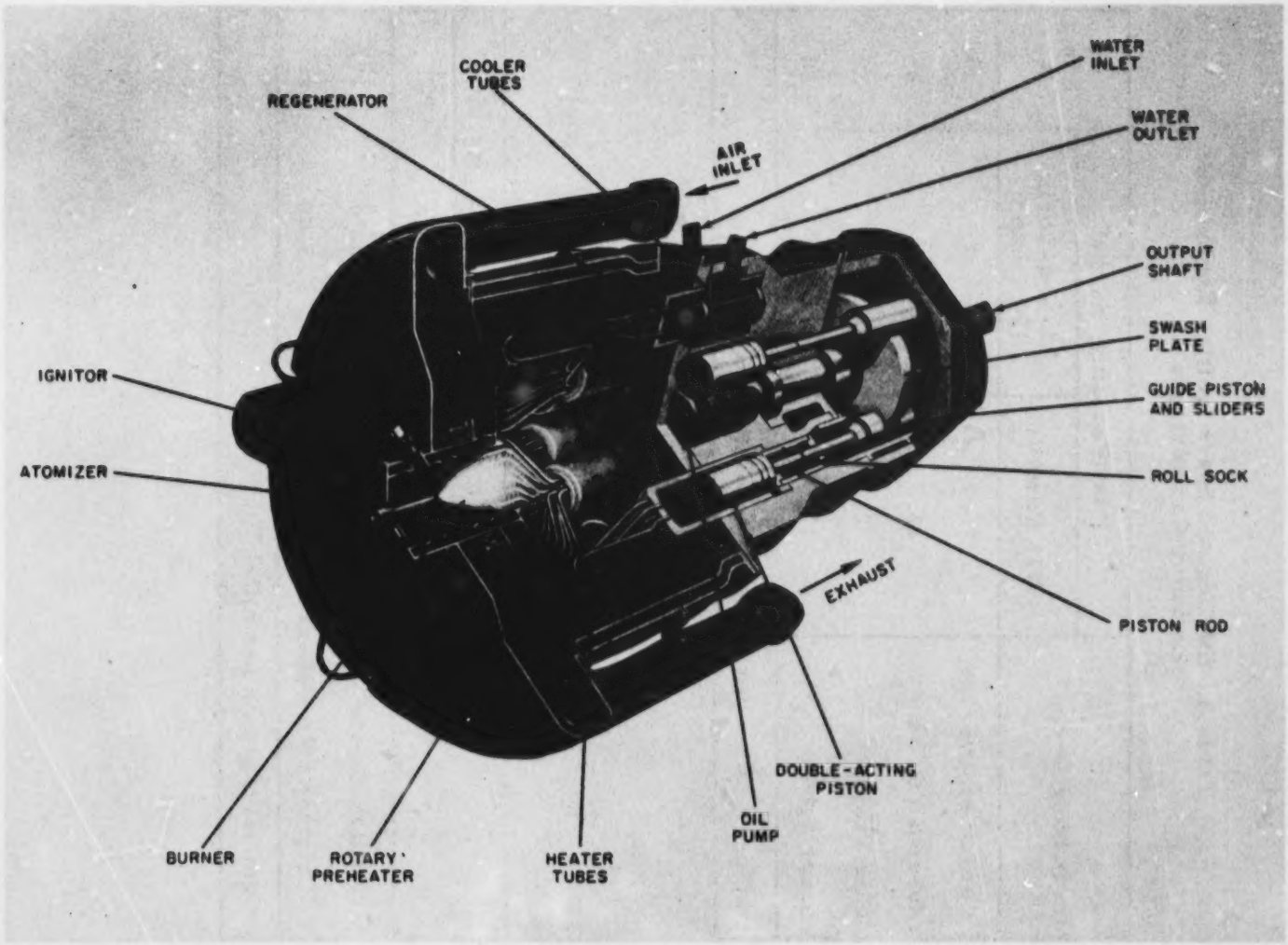

Figure 5. Philips Stirling Engine with Swash-Plate Drive

Table 3. Stirling and Spark Ignition Engine Fuel Economy Comparisons

Driving Cycle	Fuel Economy, mi/gal		Gain, %
	1976 Ford V8	Stirling-Torino (Projected)	
Consumer Average	10.7	14.7	37
Suburban Driving	13.3	17.9	35
City Traffic	8.2	11.4	39
Superhighway	13.0	16.6	28
mi/gal = miles per gallon of gasoline			

Table 4. Constant Volume Sampling Test Simulation Emissions

Comparison	Emissions, gm/mi		
	HC	CO	NO_x
Philips Engine	0.10	0.31	0.175
Original 1976 Federal Standard	0.41	3.40	0.4
gm/mi = grams per mile			

Diesel Engines

1. A number of manufacturers (including Mercedes, Peugeot and Opel) are currently marketing a passenger car powered by a Diesel engine.

2. Based on test data taken by EPA, research institutions, and engineering/manufacturing firms, light-duty vehicles powered by Diesel engines have shown emissions below the original 1975 Federal emission standards, but there are no indications as yet that this engine can adequately meet the original 1976 Federal oxides of nitrogen standard. Additionally, Diesel odor and particulates (smoke) have long been recognized as undesirable exhaust emission products. Progress toward determination of the cause of the odor has been very slow, though its control has been achieved in some engines through fuel injection system refinements.

3. The fuel economy of Diesel-powered vehicles over the Federal Emissions Test Driving Cycle is between 50 and 70 percent better than that achieved by the average 1973 model year emission certification vehicles tested at the same inertia weight. Currently, however, because installed Diesel engine power is relatively low, vehicle acceleration is significantly lower than that found with spark ignition engine-powered cars. On an equivalent performance basis, the fuel economy advantage of a higher powered Diesel vehicle would be expected to be smaller than that for current lower powered Diesel vehicles.

4. The power output per pound of engine weight of currently produced light-duty Diesel engines is considerably lower than that presently offered in spark ignition engine-powered domestic automobiles. Methods for increasing the power output per pound of engine weight include: (a) the increase of power by turbocharging or supercharging, and (b) the decrease of engine weight and bulk by a reduction in engine compression ratio and a shortened design life. At the present time, there does not appear to be any development work on any of these approaches.

Wankel (and Other Rotary Piston Engines)

1. Although production levels of rotary engine-powered cars have been rising, they represent a very small fraction of the automobile population. Currently, these engines appear principally in Mazda vehicles manufactured by Toyo Kogyo. Production levels are expected to increase with the limited introduction scheduled for the 1975 model year of the Chevrolet Vega powered by the General Motors rotary engine.

2. For a given power rating, the rotary engine is lighter and smaller than a reciprocating piston, spark ignition engine. Reductions in engine size and weight can also lead to smaller and lighter vehicles as the result of more compact packaging.

3. A manufacturing problem exists in attempts to increase production rates. Because of complex machining operations required on both the housing and rotor, production of this engine is currently limited to about 25 per hour per line (compared to piston engine rates of over 100 per hour per line). This limitation appears to have a significant impact on manufacturing costs.

4. Technological problems still exist for some engine designs. These consist of high gas seal leakage, high thermal stresses, poor low-speed fuel economy, and high exhaust emissions without aftertreatment. With aftertreatment (a thermal reactor), the Mazda rotary engine has demonstrated the ability to meet the original 1975 Federal emission standards.

Stratified Charge Engines

1. Honda has a divided-chamber version (designated CVCC) (Figure 6) of the stratified charge engine in production. Without incorporation of additional emission control systems, its CVCC engine-powered Civic vehicle met the original 1976 Federal emission standards for hydrocarbons and carbon monoxide, while oxides of nitrogen were about twice the standard. Vega and Impala vehicles achieved similar emission levels at low mileage when powered by General Motors engines modified by Honda to the CVCC configuration.

2. Army M-151 (jeep) vehicles equipped with the Texaco (TCCS) (Figure 7) and the Ford experimental open-chamber version of the stratified charge engine have met the original 1976 Federal standards with the use of an emission control system incorporating oxidation catalysts and exhaust gas recirculation. But these vehicles were unable to negotiate the high acceleration modes of the Federal Emissions Test Driving Cycle.

3. Fuel economy of the Honda Civic vehicle with the CVCC engine, as measured over the Federal Emissions Test Driving Cycle, was about ten percent lower than that of conventional Civic vehicles and 16 percent lower than that of equivalent-weight 1973 model year emission certification vehicles. A Vega vehicle with this type of engine showed fuel economy five to ten percent better than that of the standard Vega. A CVCC-powered Impala and a Texaco TCCS-powered M-151 vehicle showed equal or slightly better fuel economy compared to the respective unmodified vehicles.

4. Both open-chamber and divided-chamber engines have demonstrated a lower sensitivity to fuel octane number than the basic spark ignition engine.

5. A potential problem area for both open-chamber and divided-chamber engines is high production cost. The open-chamber engine also requires cylinder fuel injection. Additional potential problem areas

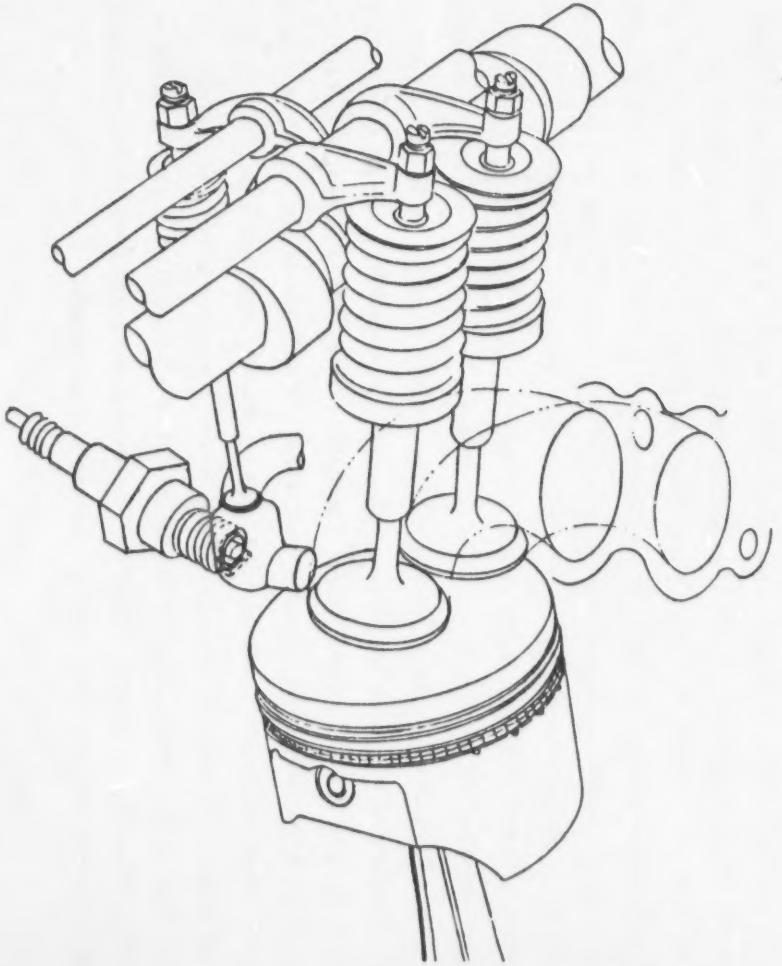

Figure 6. Honda CVCC, Divided-Chamber Stratified Charge Engine

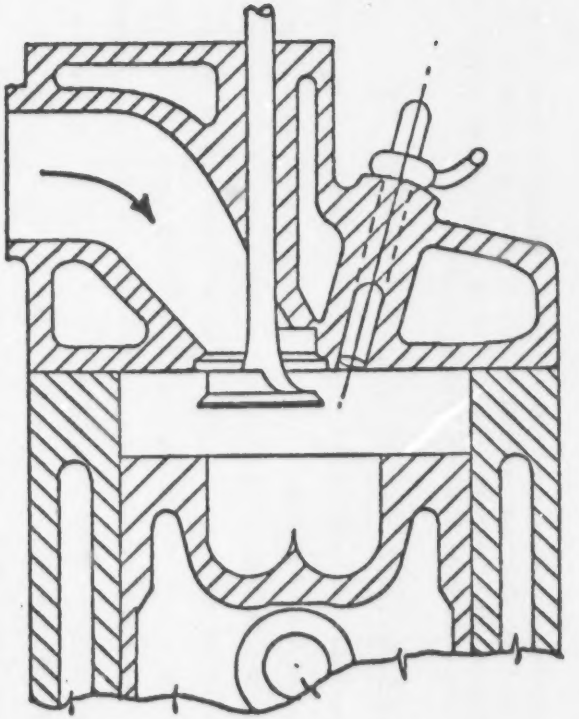

Figure 7. Texaco Cup Combustion, Open-Chamber Stratified Charge Engine

related to open-chamber engines include emission control system durability and the current inability to achieve oxides of nitrogen emission levels that meet original 1976 Federal emission standards without incurring a substantial loss in fuel economy.

COMPARATIVE REVIEW OF ALTERNATIVE ENGINES

Each of the heat engines and powerplants being considered as an alternative to the spark ignition engine for automobile propulsion has its own unique characteristics. If sufficient performance data were available, the engines could be compared readily and objectively to provide a relative ranking of these characteristics. In general, such data are limited in scope or not available for this purpose because the engines are in an early and different phase of development where more effort has been devoted to establishing proof of principle for a particular design concept rather than to establishing all of the prototype baseline performance characteristics. Therefore, comparisons are at best subjective.

Of overriding importance, however, is that each alternative engine offers the potential of meeting the original 1976 Federal emission standards, and most show reasonable progress towards these standards as shown by the representative data for selected engines in Table 5. It should be stressed that because the engines are at different stages of technological development, it is not meaningful to attempt to compare and rank them with regard to the potential for achieving the lowest possible emissions, whether for a single exhaust emission specie (e.g., hydrocarbons) or all three species.

Besides emissions, other topics of concern in selecting an engine to supplant the spark ignition engine are adaptability to mass production, purchase and maintenance costs (including durability factors), fuel consumption, fuel compatibility, weight and size impact on vehicle packaging requirements, flexibility and responsiveness to driver commands, noise, etc. Current development efforts are directed toward engine size and weight reductions that will permit engine installation in conventional automobile engine compartments. Additional effort is also being applied to ensure engine flexibility and responsiveness and to reduce noise levels.

Table 5. Selected Exhaust Emission Data, Alternative Engines

Engine	Exhaust Emissions,[a] gm/mi			Remarks
	HC	CO	NO_x	
Gas Turbine				
Chrysler engine	-0.26	3.99	2.21	Background level subtracted from measured values
Solar advanced combustor	0.11	3.34	0.34	Calculated, based on combustor tests
General Motors 225-horsepower	0.02	2.4	0.32	Chassis dynamometer tests, experimental engine
Rankine Cycle				
Water Reciprocating	0.09	0.5	0.2	Calculated, based on component tests (1972 FTP)
Stirling	0.10	0.31	0.18	Calculated, based on component tests
Diesel				
Mercedes Benz 220D	0.34	1.42	1.43	EGR and engine modifications required to reduce NO_x emissions
Wankel				
Toyo Kogyo	0.35	2.2	0.49	Low-mileage tests with thermal reactor and EGR
Stratified Charge				
Honda CVCC	0.24	1.75	0.65	Average values for 50,000-mile test car (Civic)
Ford M-151 PROCO	0.37	0.93	0.33	Based on EPA tests with catalyst and EGR

[a] 1975 Federal Test Procedure (FTP) except where noted (grams per mile).

EGR = Exhaust gas recirculation.

Mass production and the resulting purchase cost are factors that have been reviewed in screening the various alternative engines, but firm quantitative comparisons are generally not available.

This report is intended to depict the status of development of complete alternative engine systems. But it is extremely difficult to provide this information on an absolute basis because one member of the automotive industry is more advanced with respect to one engine type than others. Also, groups outside of the industry appear to be conducting more advanced work than those in the industry (e.g., on at least one type of alternative heat engine/electric hybrid) and an overseas firm is producing rotary engines while no company in the U.S. has produced any as yet. Perhaps the most informative means for illustrating this status is one which relies on subjective judgments and qualitatively relates the investment costs to knowledge generated about each alternative system throughout all phases of product development. Figure 8 shows this type of relationship for the alternative heat engines and electric and hybrid systems and shows where the conventional engine may be placed on this curve. In effect there is not a single such curve wherein each alternative system moves as development costs increase. Use of a single curve simply facilitates the comparisons.

The figure was formulated by the staff of the AAPS Division and is intended to show the relative state of development and which particular phase of development each system is in as of the end of 1973 in the U.S. The figure applies to passenger car systems.

Several conclusions can be obtained from this figure. These include:

- It takes a considerable investment of funds (and time) to gain the knowledge of each type of system that management needs to make a decision on committing a given system to production (note that the abscissa has a logarithmic scale).
- In the very early phases of development much knowledge can be obtained with the use of relatively small funds.

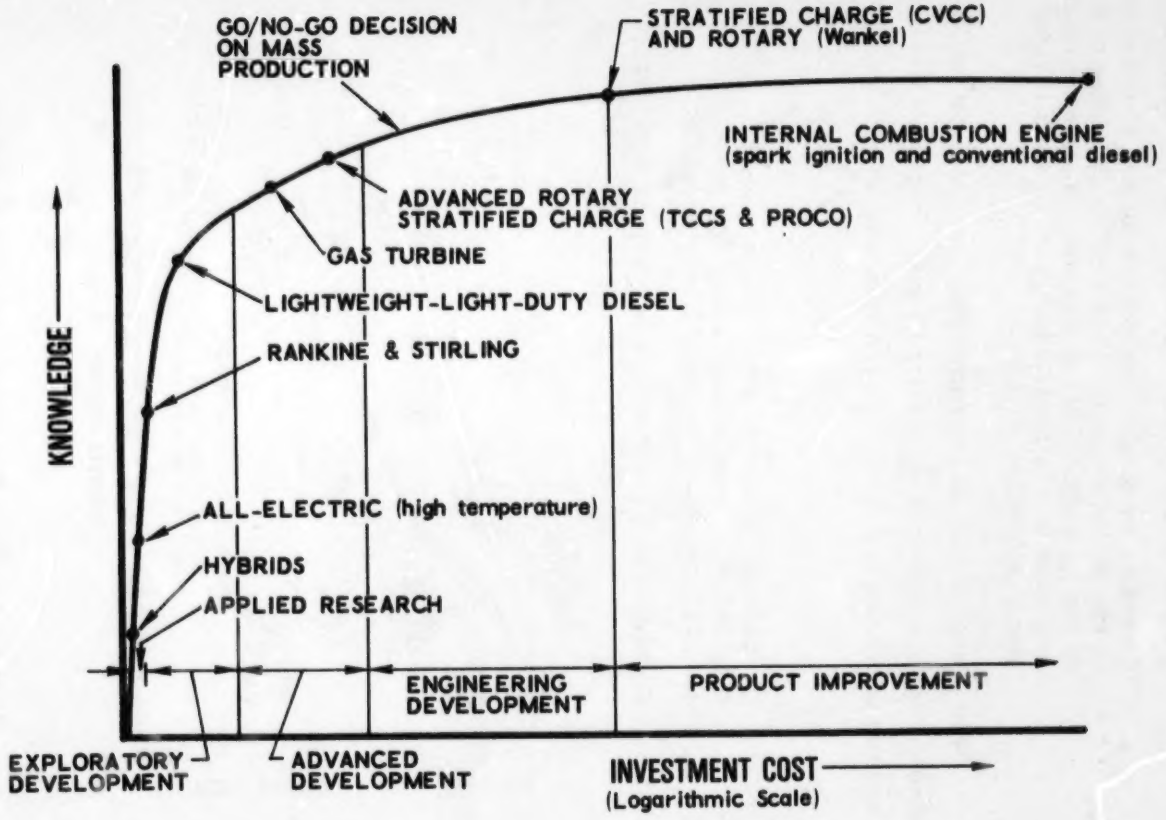

Figure 8. Knowledge Made Available as a Function of Investment in Engine Development

- As a system proceeds into later development phases, investment cost increases at rates considerably in excess of the gain in knowledge of the system.
- There is no single alternative engine that comes close to the internal combustion engine in terms of knowledge of the system. This is because the past investments in this type of engine are far greater than investments in any alternative.

With respect to fuel consumption, the data are sufficient for an illustrative comparison among various engines. Figure 9 presents measured fuel economy results for the spark ignition engine contrasted with

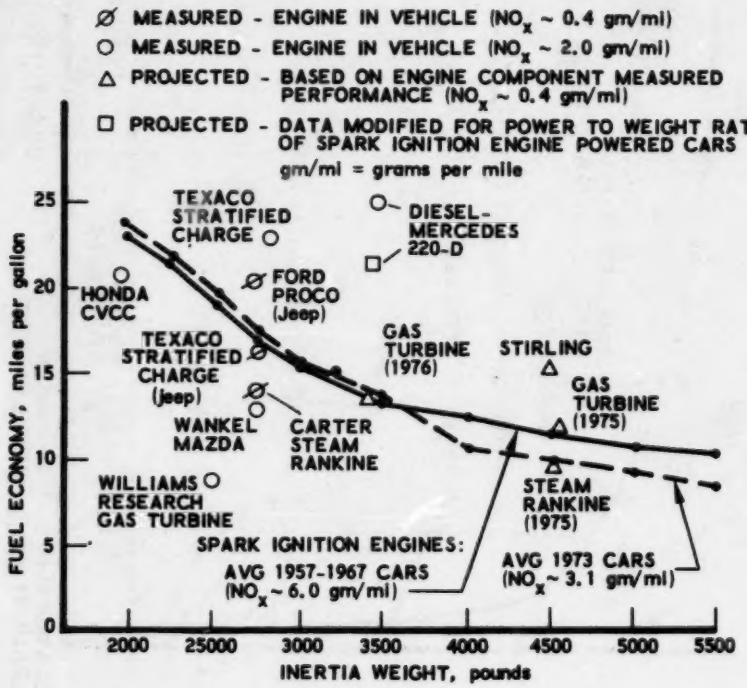

Figure 9. Fuel Economy Over the Federal Emissions Test Driving Cycle (Equivalent Gasoline Fuel)

measurements and estimates of fuel economy for alternative engines. As can be seen, some alternative engines appear capable of delivering superior fuel economy, particularly when judged against the degraded fuel economy of exhaust emission-controlled 1973 model year cars. Even on this basis an absolute comparison is difficult because the fuel economies of the internal combustion engines change with model year.

ALTERNATIVE NONPETROLEUM-BASED AUTOMOTIVE FUELS

Domestic liquid petroleum products satisfied 74 percent of the United States energy consumption in 1971; they are expected to satisfy only about one-half of the needs in 1985 and less than one-half in 2000. This excess demand-versus-supply situation provides a strong motivation for government agencies and the transportation industry (which consumes at present about 55 percent of liquid petroleum products) to investigate the potential of alternative nonpetroleum-based fuels for automotive applications. Several alternative fuels were considered as replacements for, or partial supplements to, conventional petroleum-based fuels. These were evaluated on the basis of availability, compatibility with existing distribution and storage systems (both mobile and stationary), suitability for use with personal passenger cars, relative advantages in terms of vehicle fuel economy and emissions, costs to the consumer, capital investment costs, critical research gaps, technological status, and the time scale for production implementation. A principal data source used was two AAPS-funded studies (with the Institute of Gas Technology and Exxon Research and Engineering Company) concerned with the assessment of alternative automobile fuels.

In evaluating the potential of alternative fuels for transportation, the energy source from which they are derived is a prime consideration. Sources available in the future will be coal, oil shale, tar sands, nuclear energy, and solar energy, while liquid petroleum and natural gas will be in continued short supply. Significant production of liquid petroleum fuels from coal, oil shale, and tar sands cannot be expected until the far-term (1985-2000) period.[1] Contributions to domestic energy needs from nuclear and solar energy are not expected until even later periods.

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[1] Exxon and IGT designations were: near term (1975-1985), mid-term (1985-2000), and far term (beyond 2000).

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Coal is relatively plentiful in the United States, but its availability will be limited by the mining rate. Oil shale resources are not as plentiful and domestic tar sands represent substantially lower fuel resources than oil shale.

According to estimates of the National Petroleum Council and other sources, the domestic energy resource base for these fuels is $80,200 \times 10^{15}$ British thermal units (3.21×10^{12} tons) for coal, 9549×10^{15} British thermal units (1781×10^{9} barrels) for oil shale, and 127×10^{15} British thermal units (23.5×10^{9} barrels) for tar sands. For coal resources, $39,000 \times 10^{15}$ British thermal units are proven and $41,200 \times 10^{15}$ British thermal units are reasonably assured. For oil shale resources, 116×10^{15} British thermal units are proven, 1517×10^{15} British thermal units are reasonably assured, and 7916×10^{15} British thermal units are speculative. The tar sands figure is designated as a reasonably assured resource. Recoverable reserves are less than the figures cited and depend largely on extraction economics, extraction procedures, and possible legal restraints.

Nuclear energy, if developed at the rate forecast, could indirectly benefit the transportation sector by partially relieving the electric sector from the use of fossil fuels. These benefits to the electric sector could also be supplied by solar energy, but this would require a major technology breakthrough to be of advantage to the transportation sector. Thus, solar energy cannot be considered for the near-term period (1975-1985) and may be problematical for use to the year 2000.

The evaluation of each fuel was predicated on numerous interacting factors, among which were abundance of domestic resources, technological status of production techniques, schedule for mass production, estimated capital and consumer costs, and adaptability to both internal and external combustion types of engines for automobiles (including characteristics related to fuel economy, exhaust emissions, handling, storage, and toxicity). Table 6 lists the candidate fuels and summarizes their availability and suitability as future alternatives to petroleum-based gasoline and distillate fuels.

Table 6. Summary of Availability and Suitability of Alternative Nonpetroleum-Based Automotive Fuels

Fuels	Present Energy Source	Future Energy Source	Fuel Available in Limited Quantity (Near-Term Energy Source)	Fuel Available in Significant Quantity (Future Energy Source)	Future Suitability for Automotive Use	Research Gaps in Engine Application	Factors Inhibiting Fuel Use
Synthetic gasoline and distillate hydrocarbon	Liquid petroleum	Coal, oil shale	Pre-1985	Post-1985	Excellent	More engine data	Major factors identified
Methanol,[a] Ethanol	Natural gas, liquid hydrocarbons	Coal, possibly solid waste	Pre-1985	Post-1985	Good, Fair	More engine data	Cost, performance, compatability factors
Methane (CNG or LNG)	Natural gas	Coal, possibly solid waste	Pre-1985	Post-1985	Fair	More engine data. Resolve storability problem	On-board storage, distribution network
Propane, Butane (LPG)	Natural gas, liquid hydrocarbons	Coal	Pre-1985	Post-1985	Fair	More engine data	More expensive than synthetic gasoline and similar fuels
Hydrogen	Petroleum, gas, coal, water (by electrolysis)	Coal, nuclear (electrolysis)	Post-1985	Post-2000	Fair to poor	More engine data. Resolve storability problem	On-board storage, distribution network, safety
Ammonia, Hydrazine	Same as hydrogen	Same as hydrogen	Post-1985	Post-2000	Poor	Not worth pursuing	Toxicity, safety, cost
Reformed fuels	Liquid hydrocarbons	Coal, oil shale	Post-1985	Post-1985	Fair	More engine data. Development of fuel reforming	Cost and complexity

[a]Possible application when mixed with gasoline (methanol blend).

CNG = compressed natural gas
LNG = liquid natural gas
LPG = liquid petroleum gas

Additional information is provided in Table 7 which also lists estimated fuel costs (ex tax) at the pump. It is noted that evaluations of the ability of nonpetroleum-based alternative fuels to compete in price with petroleum-based fuels are in a state of flux because of the recent fluctuations in the cost of automotive fuel. Likewise, cost estimates for alternative fuels may be revised as more data are acquired from future pilot and prototype demonstration fuel production plants.

It should also be recognized at the outset that an important factor affecting the rate of possible implementation of each of these fuels (except synthetic gasoline and distillate fuels) would be the need for a completely new nationwide specialized distribution and storage network. Undoubtedly, a dual-fuel system would be required for an extended period of time to satisfy the needs of both gasoline-fueled vehicles and new vehicles designed to use the alternative fuels.

Based on all the aforementioned considerations, it would appear that synthetic gasoline and distillate hydrocarbons manufactured from coal and shale offer the greatest promise for contributing to automotive fuel requirements in both the near-term and far-term periods. Coal-derived methanol, particularly in a methanol-gasoline blend, could be considered a secondary fuel source if certain technical problems were solved. Another alternative fuel of merit is hydrogen, but it can only be considered as a possible contributor to automotive needs in the period beyond the year 2000. The rationale for these selections is amplified in the following highlights which present the essential elements of the current status of alternative automotive fuels.

Synthetic Gasoline and Distillate Hydrocarbon Fuels

1. Synthetic gasoline and distillate hydrocarbon fuels could be manufactured from coal, oil shale, tar sands, or organic waste products. They possess the primary advantage of expected complete compatibility with existing and advanced automotive powerplants, as well as with distribution facilities down to the local gas station.

Table 7. Logistic Factors for Use of Alternative Nonpetroleum-Based Automotive Fuels

Fuel	Est. Cost at Pump in 1973 Dollars (Taxes Excluded) $/10⁶ Btu[a]	Vehicle Storage	Toxicity	Safety	Compatability with Petroleum Fuels	Status of Distribution to Consumer
Gasoline[b]	3.15 (from coal) 2.60 (from shale)	Excellent	Medium	High fire hazard	--	Existing
Distillate[b]	2.50 (from coal) 2.00 (from shale)	Excellent	Low	Low fire hazard	High	Existing
Liquid Hydrogen	7.00 (from nuclear electrolysis) 4.70 (from coal)	Poor	Low	High fire and explosion hazard	Low	Major development and investment required
Ammonia	7.65 (using hydrogen from electrolysis)	Fair	High	Moderate fire hazard	Low	Some experience in farm distribution. Major expansion required with emphasis on safety
Hydrazine	Over 20	Good	High	High fire and explosion hazard	Low	Major modifications to existing gasoline system in areas of materials compatibility and safety
Methanol	3.40 (from coal)	Good	Medium	Moderate fire hazard	High if water contamination controlled	Existing gasoline system could be used with modifications to prevent water contamination and corrosion
Ethanol	7.80 (from organic waste)	Good	Low	Moderate fire hazard	High if water contamination controlled	Same as Methanol
Methane	3.80	Poor	Low	High fire and explosion hazard	Low	About the same problem as for Hydrogen
Propane	Greater than 3.80 (from coal liquefaction)	Fair	Low	Moderate fire hazard	Low	Limited availability at present. Requires extension

[a] $/10⁶ Btu = Dollars per million British thermal units for the post-1985 period. Data are primarily from F. H. Kant, et al., Feasibility Study of Alternative Fuels for Automotive Transportation (in three volumes), EPA-460/3-74-009-4-a, Exxon Research and Engineering Company (June 1974).

[b] Currently at the pump, gasoline from petroleum at 38¢ per gallon is equivalent to $3.35/10⁶ Btu and distillate from petroleum at 37¢ per gallon is equivalent to $2.80/10⁶ Btu (taxes excluded).

2. Coal (particularly from strip mining processes) is by far the largest and most probable domestic energy resource available for synthetic fuel production, followed by oil shale. Additional domestic sources of much less potential, in terms of ability to meet projected energy needs, are tar sands and organic waste products.

3. The production cost in the post-1985 period for gasoline and distillate hydrocarbon fuels derived from oil shale is estimated to be competitive with current costs of conventional petroleum-based sources. Equivalent liquid hydrocarbon fuels derived from coal are more expensive but are also competitive. In either case, waste product disposal constitutes a serious environmental problem, with processed oil shale being the most critical concern.

4. The production economics for liquid hydrocarbon fuels derived from coal and shale will ultimately depend on (a) the efficient commercialization of various production processes currently under evaluation in laboratory and pilot-plant models, and (b) the transport distance required for raw and/or refined products. Intensive capital investment will be required if several 50,000- to 100,000-barrel-per-day plants are to be in operation in the 1980-1985 period.

5. Little information is available on the actual use of synthetic gasoline or distillates in automotive engines. A test program to verify the compatibility of these fuels with automotive engines is planned for Fiscal Year 1975 under an interagency agreement between EPA and the Bureau of Mines.

Methanol and Methanol-Gasoline Blends

1. Pure methanol has seen limited successful use with spark ignition engines powering automobiles. It offers the following advantages:

   a. An increase in power from existing engines fueled with gasoline, largely because methanol heat of vaporization characteristics lead to increases in air inducted into the engine and to increases in net work output.

   b. An increase in efficiency and in power output per pound of engine weight for new engine designs because the engine can operate at higher compression ratios than with high octane premium gasoline.

2. Certain disadvantages of pure methanol will require that careful preparation by fuel distributors and automotive manufacturers precede its

possible introduction into the retail sales market. Among these disadvantages are:

a. Fuel economy (in miles per gallon) with pure methanol is about half that with gasoline, necessitating a major increase in the size of the automobile fuel tank and modifications to the carburetor fuel jets [although the energy expended each mile (in British thermal units per mile) in powering an automobile with methanol is equivalent to the energy expended with gasoline].

b. When contrasted with gasoline, vapor pressure characteristics of pure methanol imply that there may be a greater incidence of vapor lock with current automobile fuel system designs. Also, cold start is more difficult and manifold preheating is required to ensure complete vaporization in carbureted systems.

c. Miscibility between pure methanol and water can result in the presence of water (from local atmospheric moisture) in the fuel distribution system, in the service station tanks, and in the vehicle tank, leading to possible corrosive action on metal surfaces in piping, tankage, and within the engine itself. Corrosion inhibitors may be required in the fuel to avoid this problem.

d. Synthetic methanol transport costs are expected to be higher than those estimated for synthetic gasoline because, for equal energy content, the pure methanol volume required to be piped, trucked, and stored is approximately twice that of gasoline; therefore, when distribution costs are included, the cost (ex tax) at the pump to the consumer, per unit of fuel energy delivered, is estimated to be 10 to 30 percent greater than that for synthetic gasoline from coal and shale, respectively.

e. The solvent action of pure methanol may damage paint, metal, and plastic surfaces; therefore, solvent-resistant materials must be considered for use in all applications.

3. A greater near-term advantage may accrue from the use of methanol-gasoline blends rather than pure methanol. This approach would conserve gasoline stocks to a small degree without necessitating major redesign of automobiles or engines. It should be noted, however, that even if methanol is added in a methanol-gasoline blend only to the five percent level, current automotive fuel consumption would require about five times the present U.S. methanol production.

4. As with pure methanol, methanol-gasoline blends have a higher octane rating than gasoline alone. But there are indications that the motor octane number (MON) increase is not nearly as great as that which

would be expected from measured increases in the research octane number (RON). This would indicate that engine road performance increases will not be as marked as those found in the laboratory.

5. Vapor lock and water miscibility problems would be present to a much greater degree with methanol-gasoline blends than with pure methanol. An example of these problems is the separation of gasoline and methanol in the presence of very small amounts of water, particularly at low temperatures. Solutions to these problems may be possible, but they require laboratory and road test verification.

6. The majority of published data on the application of methanol and methanol-gasoline blends to fueling automotive engines is about 20 to 30 years old. The use of new materials, engines, gasoline blends, and lubricating oils is a compelling factor for acquiring more contemporary characteristics of methanol in order to verify or invalidate older concepts regarding advantages and disadvantages of this alternative fuel. In this regard, the adaptability of methanol and methanol-gasoline blends to modern automotive systems will be explored systematically in a test program initiated by the Bureau of Mines through an interagency agreement with EPA. Other research programs investigating methanol and methanol blends are in progress, or planned, at several universities and industry research laboratories.

Methane (Synthetic Natural Gas[1])

1. Because of supply constraints of natural gas, efforts are under way to develop the technology for deriving synthetic natural gas from either coal or liquid hydrocarbons. Production levels will depend on the completion of coal gasification plants which are first expected to be in operation in the post-1980 period.

2. Liquefied gas (natural or synthetic) is more attractive than the gaseous form because of its greatly increased density (resulting in reduced storage volume requirements in the vehicle). However, the low boiling point requires application of cryogenic tank insulation techniques which add substantially to automobile tankage weight and cost relative to a conventional gasoline system.

3. Energy expenditure per mile in powering an automobile with an engine converted to operate on natural gas is approximately equal to or better than that for a similar vehicle using a modern gasoline engine equipped with emission control devices. In general, exhaust emissions with natural gas are expected to be lower than those with gasoline.

[1]Also referred to as "substitute natural gas."

4. A significant factor in the use of natural gas in place of gasoline as an automotive fuel is the reduced activity of hydrocarbon emissions in the formation of photochemical smog. Total hydrocarbon activity is four to six times less than that of gasoline.

5. Because of the difficulties in implementation of an adequate fuel distribution system throughout national urban areas, and because of the problems of storage on the vehicle, neither liquified nor compressed natural gas is considered to be a primary alternative fuel candidate for large-scale automotive use. Usage would be expected primarily for commercial fleet operations. However, synthetic natural gas may be expected to be of significance in replacing petroleum fuels for stationary electric generating power plants based on projections that, in the far-term period, 20 to 25 percent of the total gas supply may come from coal gasification.

Propane

1. Propane appears suitable for use in all of the alternative engines currently being considered. Vehicle tankage volume and weight is less than that required for methane, and cryogenic cooling is not required for storage in a liquid form if the fuel is pressurized to about 250 pounds per square inch. However, as in the case of methane, this fuel is not considered a primary alternative candidate for large-scale automotive use because of distribution and storage problems.

2. Exhaust emissions from propane show marked reductions when compared to those from gasoline, but fuel economy trends are inconsistent amongst different data sources.

3. Adequate availability of the fuel is a major problem because the major production source of propane is natural gas processing plants (a declining resource). Hence, a new raw material source (e.g., coal or oil shale) and production process would be required to increase its availability.

4. Consumer costs of liquid petroleum gas are generally similar to the price of gasoline, as of mid-1973, but gasoline is cheaper for powering an automobile on the basis of energy expended per mile. Furthermore, if in the future propane is manufactured synthetically from coal, costs to the consumer are projected to be greater than for synthetic methane (and certainly greater than for synthetic gasoline).

Ethanol and Ethanol-Gasoline Blends

1. Ethanol has been demonstrated to be compatible as a motor fuel with present vehicles. In many parts of the world, it has been blended in

concentrations varying between ten and 20 percent to alleviate gasoline shortages. Pure ethanol or blends with gasoline have essentially the same usage problems cited for methanol.

2. The economics and instability in the price of ethanol production based on fermentation of agricultural raw materials and the poor fuel economy are additional major factors tending to limit its use. Ethanol-gasoline blends have been considered, but the cheaper and equally efficient methanol-gasoline blends are preferred.

Hydrogen

1. Success has been attained in carrying out the necessary mechanical conversions to enable conventional gasoline engines to operate on hydrogen. Indications are that extremely low exhaust emission levels are possible. Fuel economy on an energy-expended-per-mile basis is found to be comparable to that for gasoline, but maximum engine power output for a given engine size is reduced significantly.

2. A major technical drawback with hydrogen as fuel for the automobile is the problem of storage on the vehicle. Storage in compressed gas form is not practical, and even in cryogenic liquid form storage is complex and expensive, requiring a tank capacity three and one-half times that needed for gasoline on an equivalent energy basis. Research is under way to evaluate an alternative reduced-volume storage approach using metal hydrides; a means of also reducing the storage weight will be necessary before this technique can be considered practical.

3. Additional major obstacles to using hydrogen as a universal fuel concern the energy supply adequacy for its manufacture as well as very high costs to the consumer. Nuclear power will be a necessary factor in ensuring an adequate supply of energy for production of hydrogen by water electrolysis. On an equivalent energy basis, liquid hydrogen cost to the consumer will be much greater than the cost of gasoline or distillate derived from coal. Much of this cost is attributable to significant cost items connected with the liquefaction of hydrogen and its subsequent transportation to, and storage at, retail outlets.

4. Even if costs are reduced, hydrogen appears to be a possible fuel only for the post-2000 period. The massive capital requirements for manufacturing plants and distribution facilities, and the extensive period needed for actual construction activities, preclude any earlier consideration of this fuel as a major contributor to passenger car needs.

Ammonia

1. The interest in ammonia as an engine fuel stems from the consideration that it allows the storage of hydrogen in nitrogen hydride form at relatively low pressures without some of the fire and explosion hazards associated with pure hydrogen. But the extreme toxicity of ammonia, combined with expected high consumer costs, does not hold much promise for this fuel even for the far-term period.

Hydrazine

1. For the very same reasons cited for ammonia, hydrazine is considered unsuitable as an alternative to petroleum-based fuels.

Fuels Reformed On the Vehicle

1. One approach which is being investigated as a means of extending the lean operating limits of gasoline engines in order to achieve low exhuast emissions is the incorporation of a fuel reformer device to chemically convert all or a portion of the engine's fuel requirements from gasoline (or any liquid hydrocarbon fuel) to a gaseous product (principally hydrogen) prior to induction into the engine. Initial exploratory tests have indicated marked reductions in carbon monoxide and oxides of nitrogen exhaust emissions at very lean air-fuel ratios, but these positive factors are offset by high hydrocarbon exhaust emissions. Fuel economy is projected by some investigators to be equal to or better than that obtainable with a gasoline-powered engine.

2. Fuel-reformer concepts are still in the exploratory, proof-of-principle, or feasibility determination stage. A number of critical data gaps must be filled before the potential of reformed fuels can be fully assessed. NASA has been funding the Jet Propulsion Laboratory to acquire data and prove concept feasibility, and EPA is providing supplemental funding for this work in addition to other contractor-supported programs for evaluation of similar concepts.

ELECTRIC AND HYBRID POWER SYSTEMS

Electric and hybrid power systems are unique alternatives to heat engines for automotive propulsion. The extensive use of electric vehicles would shift the burden of controlling exhaust emissions from motor vehicles to stationary electric generating plants supplying energy for recharging batteries. Furthermore, the current use of petroleum-based fuels for automotive propulsion could be diminished and personal transportation energy needs could be supported to a large degree by coal or nuclear resources.

The basic powerplant in electric vehicle designs consists of one or more electric motors and controllers, perhaps a transmission or other gears, and a battery system. Lead-acid batteries have been used in most cases, and the direct current electric brush motor is used by an overwhelming majority of vehicle designers and fabricators. In some systems, regenerative braking is used which causes the motor to operate as a generator, permitting recharging of the battery as the car decelerates. Figure 10 illustrates the main components of an electric car drivetrain in schematic form.

Currently, a major problem is the limitation on the amount of energy and power that can be delivered by a given-size battery; this limitation has a direct effect on vehicle range and acceleration. Evidence of this problem is seen in the restricted operation of contemporary electric vehicles. Analytical studies have shown that battery requirements for powering a full-performance family car are a specific energy density of about 135 watt-hours per pound to satisfy vehicle range, and a specific power density of about 95 watts per pound to satisfy vehicle acceleration. Current battery capabilities (Table 8) approach the power density requirement but fall far short of the energy density requirement. With a compact electric car, travel distances comparable to those for a heat engine car (without refueling) cannot be approached even with a battery system weighing about one-third of the vehicle curb weight.

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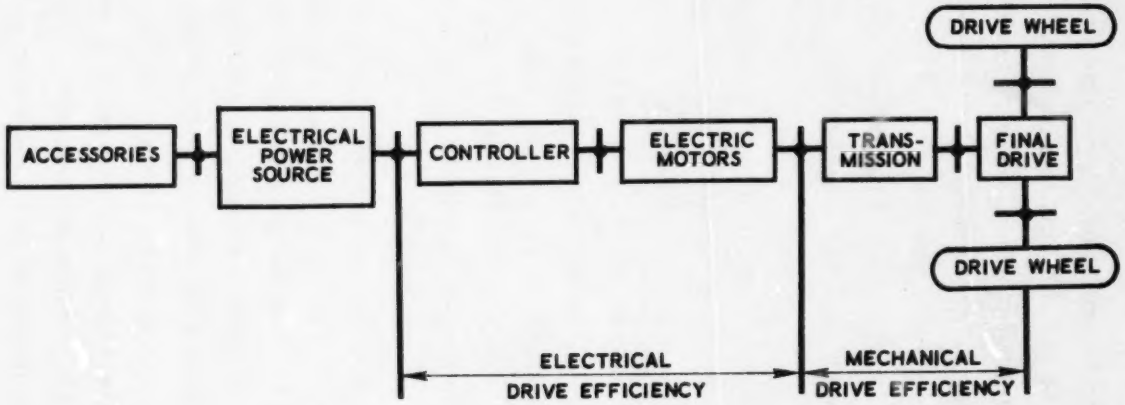

Figure 10. Main Components of an Electric Car Drivetrain

Table 8. Characteristics of Currently Available Secondary Batteries

Battery Type	Specific Energy Density, w-hr/lb	Energy Density, w-hr/in^3	Specific Power Density, w/lb	Approx. Relative Cost	Remarks
Lead-acid	20	2.0	100	1	Standard
Nickel-iron	13	1.2	60	3	Excellent life, poor maintenance
Nickel-cadmium	13	1.1	80	20	Good cycle life. Cadmium supply limited

w-hr/lb = watt-hours per pound w/lb = watts per pound
w-hr/in^3 = watt-hours per cubic inch

When promoting a new battery for development, with intended application to electric vehicles, the technical comparison is most often based on specific energy density. As electric vehicle programs proceed, other factors, implicit in the design of battery systems, must be considered. One objective of system design would be to reduce vehicle weight and to minimize influences such as drag, frontal area, acceleration, and peak cruise speed, which would allow a reduction in battery energy usage.

The problem of adequate operating range for electric vehicles will remain until low-cost, high-capacity batteries become available. In the interim, other concepts have been examined in the search for a low-pollution vehicle that could satisfy personal transportation needs. One such concept that has received the attention of automobile designers in the last five years is the hybrid vehicle--a vehicle combining various power delivery systems in the powertrain to use each form of power most effectively. The most common form of system operation that has been studied for hybrid heat engine/battery and hybrid heat engine/flywheel vehicles relies on the heat

engine just to supply energy for vehicle cruise and for recharging the battery or flywheel. The additional power needed for vehicle acceleration is supplied by the battery or flywheel. With this form of heat engine operation, the hybrid concept offers the possibility of reduced mobile emissions. A shift of exhaust emissions and energy source to stationary electric generating plants, as in the case of electric vehicles, would be possible only if the energy for recharging the battery or flywheel was available from an external stationary power source, and the heat engine was then used only for supplying emergency power or for extending vehicle range on an infrequent basis.

Hybrid vehicle powertrain concepts can be grouped into two broad classes (Figure 11). The first class, the series configuration, is characterized by the principle that all the energy flowing from the heat engine to the vehicle's rear wheels first passes through an intermediate energy conversion device or devices.[1] The second class, the parallel configuration, is characterized by the principle that some of the energy flowing from the heat engine passes directly to the rear wheels, with the balance routed in a parallel path through an energy conversion device or devices.[1]

A status review has been made of automotive electric and hybrid power systems in this country and, where information was available, in foreign nations. A number of prototype vehicles have been built with private capital, and, in some cases, Federal funding has been used to evaluate and test these systems. In particular, the results derived from EPA-funded programs were reviewed within the context of the design goals established for its AAPS Program for personal passenger cars. The following highlights present the essential elements of this review. In addition to the technical problems noted, estimated high manufacturing costs will likely be a factor inhibiting the widespread application of these systems.

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[1] Generator, motor, and battery in the electric system, or flywheel and transmission in the inertial system.

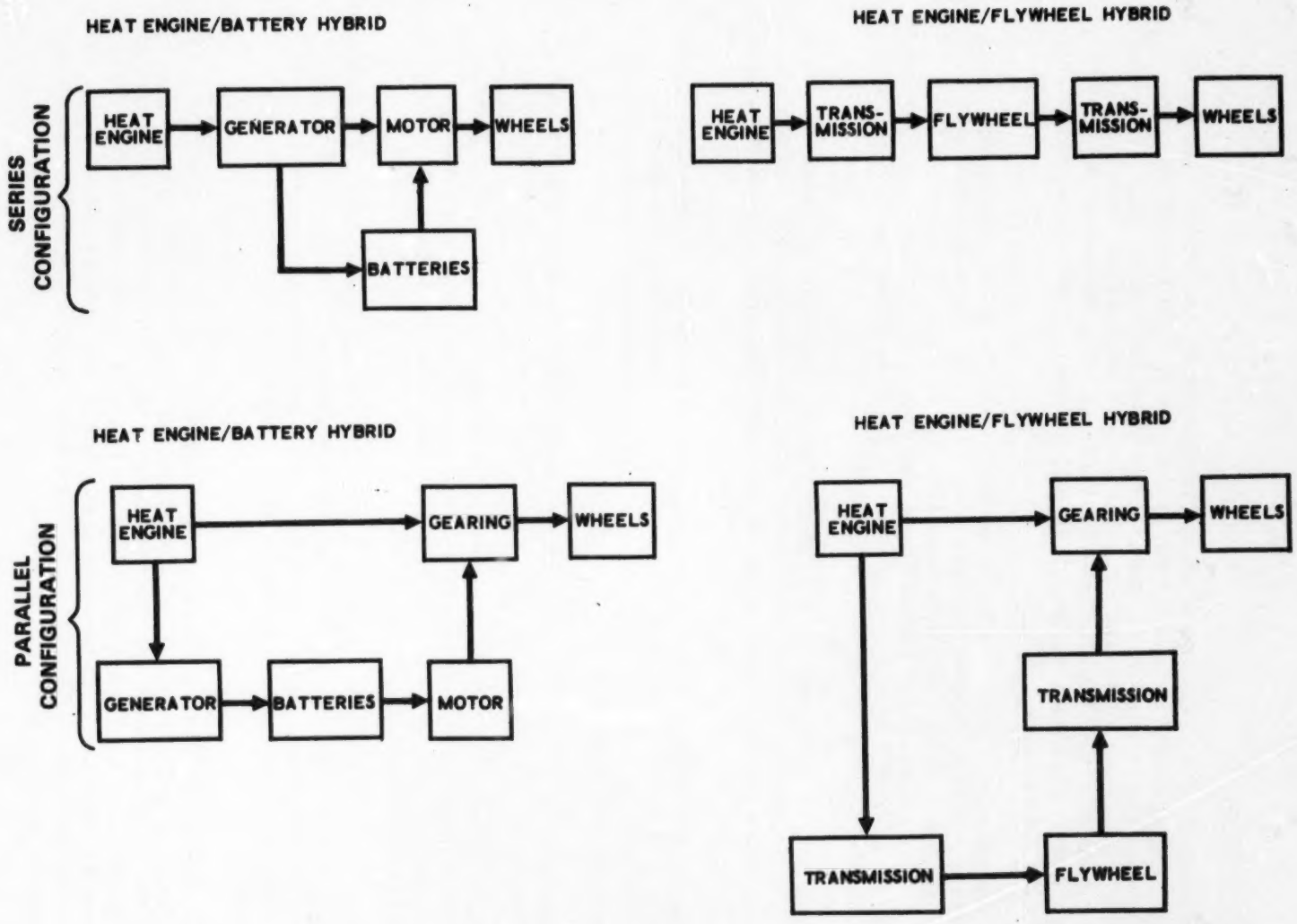

Figure 11. Simplified Schematics, Heat Engine Hybrid Vehicle Powertrain Concepts

Electric Vehicles

1. In general, the majority of electric vehicles do not perform up to heat engine vehicle capabilities--particularly with respect to maximum acceleration, speed, range, and hill-climbing ability, as well as to passenger space and accommodations such as air conditioning and heating. The usual maximum speed is 30 to 50 miles per hour, and range is usually limited to 50 miles under conditions of optimum cruise speed.

2. An additional problem with the electric vehicle is the power and time needed for recharge of the batteries. Vehicle usage will be limited unless provisions are made for exchange of depleted batteries for fresh batteries. The capability of residential electrical grids to supply large power levels during daytime for a large number of electric vehicles may be also a problem.

3. In selecting batteries for electric vehicles, a dominant parameter has been purchase cost. Consideration must be also given to battery replacement costs and operating costs. For this reason, lead-acid batteries are almost universally used.

4. No one battery has been developed yet to satisfy the combined design requirements for low cost, long lifetime, high energy density (for vehicle range), high power density (for vehicle acceleration), and ease of maintenance.

5. For near-term applications, nickel-zinc batteries offer higher energy density possibilities, but cost and nickel availability are drawbacks for supplanting lead-acid batteries (nickel-cadmium batteries are even more expensive). For far-term applications, the zinc-chlorine and alkali-metal/high temperature battery systems, with significant increases in energy and power density capabilities, appear promising if development goals are achieved.

6. Work on batteries for electric vehicles is accelerating abroad. The major activities are in the Federal Republic of Germany, Japan, the United Kingdom, and the U.S.S.R. In each case, the government is either formally participating in or is influencing the direction of the work.

7. Excluding the special-purpose applications of golf carts, electric fork lifts, and delivery vans, no major production of electric passenger vehicles is expected for the next ten years. This picture could change, should there be a major gasoline shortage, a restriction on operating conventional vehicles in some areas due to air quality constraints, or a breakthrough in battery technology which would allow much improved vehicle performance and range.

Hybrid Heat Engine/Battery and Hybrid Heat Engine/Flywheel Vehicles

1. The range limitations of electric vehicles are not found in the hybrid heat engine vehicle concept. The hybrid vehicle under discussion uses a small heat engine to provide road cruising power, with acceleration power requirements provided by a battery in the case of an electric energy storage hybrid, and by a flywheel in the case of an inertial energy storage hybrid. By so restricting the operation of the heat engine, early studies anticipated significant reductions in exhaust emissions without the need for complex, costly exhaust treatment devices, but results to date have not verified this expected performance.

2. EPA contracted with several companies in the 1970-1972 period to perform evaluations of hybrid battery and flywheel systems. This effort encompassed the analysis and test of hybrid systems as well as associated components.

3 Elements of the TRW electromechanical transmission (heat engine/battery hybrid) were assembled into a breadboard prototype unit and tested as a complete integrated system. Powertrain efficiency was found to be below predicted values (though possibly correctable through redesign), and exhaust emissions were reduced to or below the level of the original 1976 Federal exhaust emission standards only by the use of an exhaust emission control system consisting of exhaust gas recirculation, tricomponent catalysts, etc.

4. The Minicar, Inc., hybrid heat engine/battery-powered car was deficient in meeting performance goals, and exhaust emissions were not reduced to acceptable levels.

5. Petro-Electric Motors has an operable hybrid heat engine/battery-powered automobile which is undergoing test and evaluation at EPA laboratories under the Federal Clean Car Incentive Program.

6. The Aerospace Corporation analytical study of hybrid heat engine/battery-powered vehicles showed that, with a spark ignition engine, exhaust emissions could meet the original 1976 Federal exhaust emission standards only by the use of aftertreatment devices in the exhaust, along with engine modifications. In comparison to the conventional automobile, no improvements in fuel economy were found. Similar conclusions were arrived at by Lockheed in its analysis of a hybrid heat engine/flywheel system.

7. The General Motors Stir-Lec I automobile (hybrid heat engine/battery) achieved very good fuel economy, but proved to be very limited in acceleration level and peak speed. Exhaust emissions (except for oxides of nitrogen) were reduced, but not enough to meet original 1976 Federal standards.

8. Tyco concluded that a commercial state-of-the-art SLI (starting-lighting-ignition) lead-acid battery was unsuited for hybrid vehicle use because of life limitations, although required power levels were achieved. Research tests with a revised design showed improvements in meeting required EPA lifetime.

9. TRW/Gould also demonstrated that while a commercial state-of-the-art SLI lead-acid battery approached required EPA design power levels, it lacked the required lifetime. In a research battery design, TRW/Gould achieved the required power density, but lifetime goals were still not met.

10. Lockheed concluded that 4340-grade steel was the most cost-effective material for a flywheel in a disc configuration. E-glass and S-glass materials were found to be best suited for bar-type flywheel geometries. In tests to failure, the steel wheel exceeded specified peak speeds, while the glass materials fell short of design goals.

11. The Johns Hopkins University Applied Physics Laboratory tested advanced flywheels in filamentary and composite rod/bar configurations with mixed results. Single-strand boron filaments, small graphite/epoxy composite rods, and small R-glass/polyester composite rods exceeded energy storage design goals, but the larger one-pound S-glass/epoxy and graphite/epoxy composite bars failed to achieve design goals; this was attributed to inadequate material processing techniques.

12. Sundstrand determined that a combination of mechanical, hydromechanical, and hydrostatic transmissions is a practical means of providing power for the flywheel, heat engine, and drive wheel links in a hybrid heat engine/flywheel-powered car. Computer simulation of vehicles driven over the Federal Emissions Test Driving Cycle showed no fuel economy advantage for the hybrid-powered automobile when compared with a conventionally powered automobile. Mechanical Technology, Inc., in its transmission study, arrived at conclusions similar to Sundstrand.

13. Although not all of the goals were met, the EPA-funded programs resulted in some technology advancements, a much clearer definition of critical problem areas, and the establishment of preferable system operating modes. While the hybrid vehicle has proven to be technically feasible, it is a complex costly system when configured to match the performance of conventional internal combustion engine-powered vehicles.